Footprint-Based 3D Generalization of Building Groups for Virtual City Visualization

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Abstract - **This paper proposes a footprint-based generalization approach for 3D building groups in the context of city visualization. The goal is to reduce both geometric complexity and information density, meanwhile maintaining a rather recognizable shape. The emphasis is placed on converting 3D generalization tasks into 2D issues via buildings' footprints. In order to find suitable units for footprint projection and generalization, which should hold both semantic meaning and simple geometry, a meaningful partition is firstly introduced (from CityGML building models). For roof generalization, a new perspective is presented: to divide a building model into Top + Body, so that the Top part could be transplanted onto the extruded model by displacement. Two algorithms are developed for two types of building groups: one with a minor height difference and the other with a major height difference. For the former one, the outer units are detected and aggregated to represent the whole group. For the latter one, an iteration of aggregation is performed on subgroups. Each time the highest unit and its neighbors compose the subgroup. The algorithms are tested on two building groups and one part of a 3D city model.**

Keywords-3D generalization; building group; footprint; city visualization

I. INTRODUCTION

3D city visualization requires different representations of building models at different Levels of Detail (LoDs) to satisfy different scales and application needs. These LoDs should be generated automatically by specific generalization procedures. Generalization has a long history in cartography [1], with the goal of emphasizing the most important map elements while still representing the world in the most faithful and recognizable way. 3D building generalization in city visualization shares the same goal, but should consider both geographical and 3-dimensional information.

As discussed and listed in [2], unlike 2D maps that have standard official scale series, there are no generally agreed LoDs for 3D buildings. Including the four LoDs defined by CityGML (City Geography Markup Language) [3], the existing definitions of LoDs for 3D buildings only differentiate by 3D details. That is to say, they hardly respond to geographical generalization, like the generalization regarding a group of 3D building, where topological relations should also be considered. This seems to lead more attention to single building generalization.

A number of algorithms have been developed for 3D building generalization [4-13]. Most of those algorithms deal with single buildings [4-11]. Generalization of building groups is seldom addressed [12, 13]. In 3D city visualization, the goal of generalization is not only to simplify individual objects, but also to achieve better cognition by emphasizing important features. Thus, there rises a generalization need for building groups. Both 3-dimensional detail and geographical relations should be taken into account. More generalization operations like selection, aggregation, typification and their combinations are expected.

Footprint has been serving as the connection between 2D and 3D. Plenty of block models of buildings were extruded from cadastral maps using their footprints and heights. But more detailed models couldn't be acquired in this way. Therefore, a question rises here: how can we translate 3D building generalization issues into 2D scope for generalizing more detailed 3D building models?

This paper is organized as below: related work is first discussed in Section II. Section III introduces the idea of partitioning a 3D building model into suitable units for footprint-based generalization. Generalization algorithms for two types of building groups are presented in Section IV. Experimental results are given in Section V. Section VI concludes the paper.

II. RELATED WORK

Compared with map generalization techniques in 2D, generalization in 3D is still in its infancy [14]. Different from general 3D models, most 3D building models are already low-polygon objects, so generic geometrical simplification techniques from Computer Graphics seem to be of little use. Besides, parallel and orthogonal properties of buildings need to be respected during simplification. Therefore, algorithms for 3D building generalization need to be specifically designed [14]. Thiemann proposed to segment a building into basic 3D primitives [4], and to decompose the whole generalization process into segmentation, interpretation and generalization phases [5]. Mayer [6] and Forberg [7] developed scale-space techniques for simplifying buildings, partly based on the opening and closing morphological operators. Kada proposed to define parts of simplified buildings as intersections of half-planes [8] and to divide buildings into cells and to detect features by primitive instancing [9]. Without semantic information, these methods mainly detect building features based on pure geometry.

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By taking semantic information into account, Fan et al. [10] proposed a method for generalization of 3D buildings modeled by CityGML from LoD3 to lower LoDs. Their research showed that good visualization properties could be obtained by only using the exterior shell of the building model that drastically decreases the required number of polygons. Fan and Meng [11] extended their work to automatic derivation of LoDs for CityGML building models staring from LoD4. However, the above mentioned methods are all limited to generalization regarding single buildings.

Anders [12] proposed an approach for the aggregation of linearly arranged building groups. Their 2D silhouettes, which are the results of three orthogonal projections, are used to form the generalized 3D model. Guercke et al. [13] studied the aggregation of LoD1 building models in the form of Mixed Integer Programming (MIP) problems.

Techniques start emerging for generalizing 3D building groups in the context of city visualization. Glander and Döllner [14] proposed cell-base generalization by maintaining a hierarchy of landmarks. In each cell, only landmark buildings can be seen, the other buildings are replaced by a cell block. In the work of Mao et al. [15], buildings are divided into clusters by road network, and grouped with close neighbors in each cluster. However, only LoD1 buildings were handled.

III. PARTITION OF BUILDING MODEL

Our approach places the emphasis on translating 3D generalization into 2D scope. The strategy is to generate footprints of 3D buildings, perform 2D generalization on their footprints, and then extend the result to 3D. The main issue is how we extend the result to 3D without losing recognizable features like differentiated height and roof. Therefore, a meaningful partition is proposed at first, so that each footprint can carry feature information.

An implementation of partition is presented using building models encoded by CityGML [3], which supports coherent modeling of semantics and geometrical/topological properties. With semantically structured buildings models, generalization can be facilitated a lot. However, a building still can be structured in plenty of forms that make a uniform projection of footprint very difficult. Stricter rules are needed to form buildings into favorable partitions.

A. *CityGML Building Model at LoD2*

CityGML defines a standard for ontology of buildings at 4 different LoDs. At LoD1, 3D buildings are represented by block models with flat roofs. At LoD2, 3D buildings have differentiated height and roof structures. LoD3 models are detailed architectural models with openings like windows and doors. LoD4 completes a LoD3 model with interior structures.

This paper uses CityGML LoD2 building models for the partition and generalization. LoD1 block models are hardly recognizable; highly detailed models at LoD3 and LoD4 are too costly and normally only used for landmarks.

Before partitioning, we should be aware of the possible elements in such a model. So we draw a UML diagram of building model exclusively for LoD2 (Figure 1) according to the CityGML encoding standard [3]. The pivotal class is the abstract class *_AbstractBuilding*, which is specialized either to a *Building* or to a *BuildingPart*. Each can contain 3 types of properties: text attribute, pure geometry, and semantically structured geometry. The last one is the essential for our footprint-based generalization.

B. *Partition Rules*

The goal of partition is to get a well structured building in both semantic and geometric sense, so as to extract suitable unit for footprint projection and generalization. The unit should have meaningful geometry and be good for computation. The rules are introduced as below:

- If a *Building* is composed of unconnected segments, partition them into different *Buildings*.

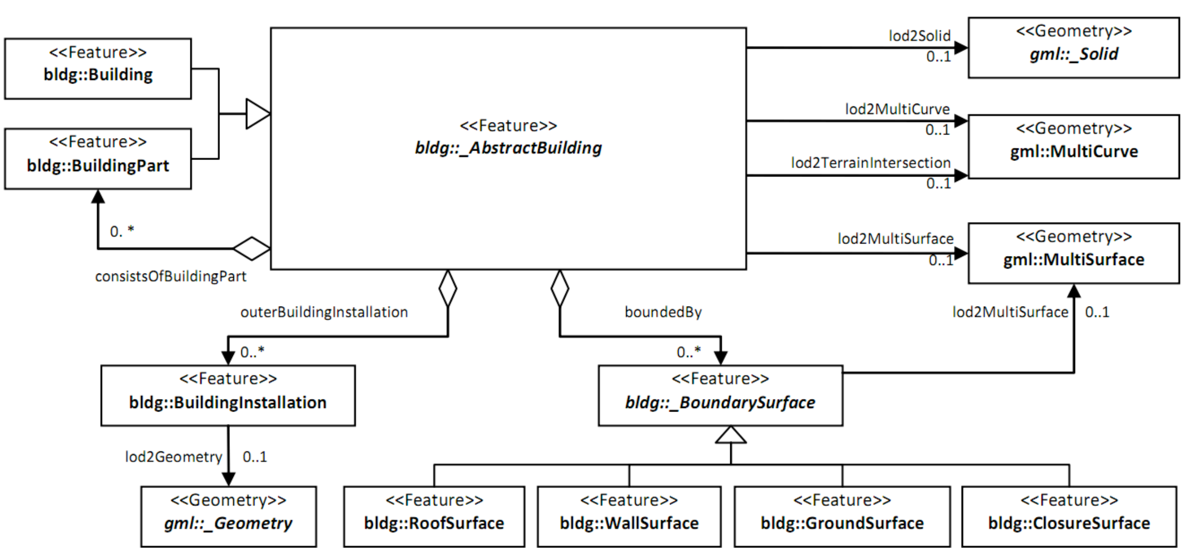

Figure 1. UML diagram of CityGML's building model at LoD2 (based on CityGML standard [3])

- If a *Building* is composed of structural segments differing in e.g. height or roof type, partition them into different *BuildingParts*.
- If a *Building/BuildingPart* has smaller components which are not significant as a *BuildingPart* (e.g. chimneys, dormers, and balconies), partition them into *BuildingInstallations*.
- If a *Building/BuildingPart* has geometries without semantic information, partition them into pure geometry.
- If a *Building/BuildingPart* has *_BoundarySurfaces* and includes *BuildingParts* at the same time, partition the *_BoundarySurfaces* into a new *BuildingPart*.
- If a *Building/BuildingPart* includes only one *BuildingPart*, aggregate the included *BuildingPart* into its parent *Building/BuildingPart*.
- If a *Building* has *_BoundarySurfaces*, there must be a *WallSurface* starting from and orthogonal to the ground plane; otherwise, partition this *Building* as a *BuildingInstallation* into another *Building*.
- If a *BuildingPart* has *_BoundarySurfaces*, there must be a *WallSurface* starting from and orthogonal to the ground plane; otherwise, partition this *BuildingPart* into a *BuildingInstallation*.
- If a *Building/BuildingPart* has unconnected or self-intersected *WallSurface*, partition it into more *BuildingParts*.

C. Beneficial Attributes

After employing the partition rules, beneficial attributes can be obtained:

- In a *Building* tree, all the leaf nodes must have *_BoundarySurfaces*; no branch nodes can then have *_BoundarySurfaces*.
- If there are *_BoundarySurfaces*, there must be a *WallSurface*; other types of surfaces are optional.
- A *WallSurface* must start from and orthogonal to the ground plane.
- The orthogonal projection of *WallSurfaces* of each leaf node form a simple polygon or polyline.
- Each leaf node only has one height.

A leaf node can contain text attributes, pure geometry, *BuildingInstallations* and *_BoundarySurfaces*, but only *_BoundarySurfaces* will be selected to form a basic unit of generalization. The term *unit* will be used in the following discussion, referring to a leaf node of a building tree only consisting of *_BoundarySurfaces*. Two examples are given in Figure 2.

IV. GENERALIZATION OF BUILDING GROUPS

In a building group, the adjacent buildings can be connected or disjoint. In this paper, we only deal with the ones with connected buildings.

There exists building groups with various features. They can hardly be generalized by a uniform method. Since height has significant influence on visual perception, we address two types of building groups in this paper: one with a minor difference in height (buildings that all look similar) and the other with a major difference in height (that include a significant building at city level).

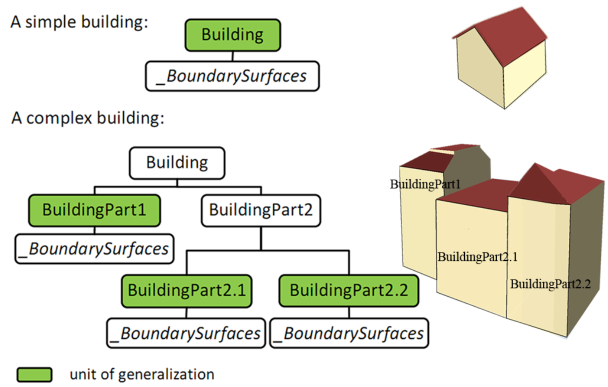

Figure 2. Two examples of building tree for generalization

A. Generating Footprints

Based on the partition discussed in the previous section, the first performed generalization operator is selection. For each *unit*, only *_BoundarySurfaces* are selected. Among *_BoundarySurfaces*, only *WallSurface* will be selected for generating footprint. However, the roof information will be lost during this projection of footprint. Another important issue is how we generalize roofs.

B. Handling Building Roofs

A common way of roof generalization is by primitive matching of different roof types. But type detection is a costly (most often manual) and uncertain process depending on the given types and lots of parameters. In CityGML building models, roof surfaces are separated from walls, but roof type is not always available in attributes. Even if given the roof type, the rebuilding of roof after extrusion would be another difficulty without knowing parameters.

Since an extruded model is usually a prism, if the original model could be divided into a top part and a prism body, the top part could be easily transplanted to the extruded model and could also be generalized with adjacent roofs. Therefore, we propose a way of dividing a building model into *Top* + *Body*. For a building, if all of its walls end at the top in the

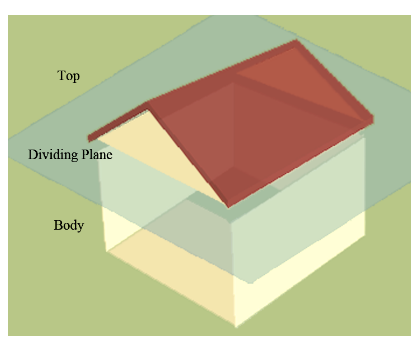

Figure 3. An example of dividing a building into *Top* + *Body*

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same horizontal plane, the *Top* only consists of its roof; otherwise, the *Top* consists of its roof and the end walls. An example is given in Figure 3.

C. Generalization of Building Groups with a Minor Difference in Height

For a building group with a minor difference in height, we believe its outer feature could represent the whole group to a certain extent, like in large scale visualization.

Therefore, inner *units* can be eliminated. Outer *units* can also be aggregated. If there are no inner *units*, aggregation can be directly performed on all *units*. If aggregated *units* have non-flat roofs, two levels of aggregation can be achieved. The original roof structures can be preserved based on the approach introduced in subsection A. They can be generalized to flat roofs as well.

Our generalization operations start from LoD2 but won't lead to LoD1 block models. Instead of using the term LoD, we use GeoLoD (Geographical Level of Detail) to denote the generalization results. Three GeoLoDs can be generated. At GeoLoD1, a building group is a prism model which conveys its outer shape. At GeoLoD2, a building group is a GeoLoD1 model added with differentiated roof. At GeoLoD3, a building group is represented by all its outer *units*. The main flow of the algorithm is depicted in Figure 4.

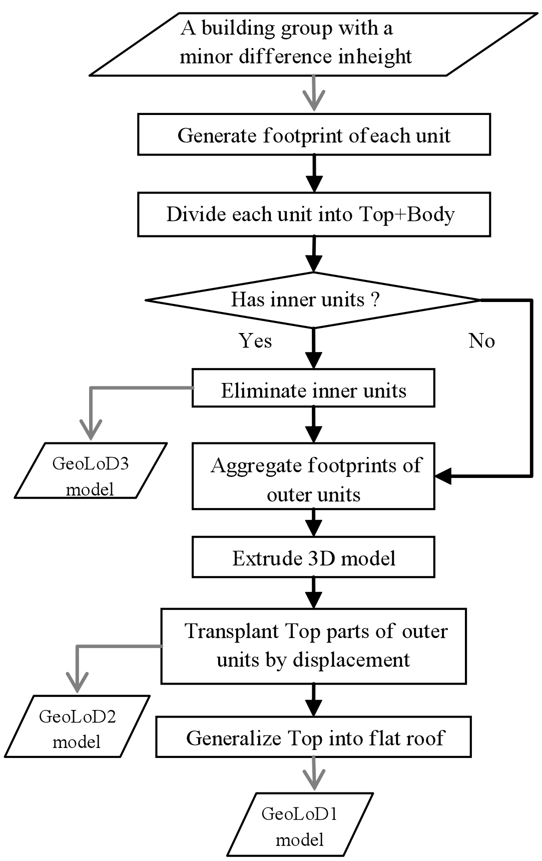

Figure 4. The main flow of the generalization algorithm for a building group with a minor difference in height

D. Generalization of Building Groups with a Major Difference in Height

For a building group with a major difference in height, the generalization will be performed on its subgroups.

A subgroup is composed of a center *unit* and its adjacent neighbors. Each time the highest *unit* will be chosen from the unprocessed *units*. If this *unit* is much higher than its neighbor, they should not be aggregated. We use the term *coequal* in this paper to indicate that the height difference in two *units* can be ignored, that is to say, they can be aggregated. *Coequal units* are defined as below:

Given two units $\boldsymbol{U_1}$ *with height* $\boldsymbol{h_1}$ *and* $\boldsymbol{U_2}$ *with height* $\boldsymbol{h_2}$*, if they satisfy the constraint as in (1),* $\boldsymbol{U_1}$ *and* $\boldsymbol{U_2}$ *are coequal, where* $\boldsymbol{Th_1}$ *is a predefined variable as the threshold.*

$$1/\boldsymbol{Th_1} < \boldsymbol{h_1} / \boldsymbol{h_2} < \boldsymbol{Th_1}, \tag{1}$$

When merging two adjacent and coequal *units*, either height of the original *units* can be assigned to the new *unit*. If the lower *unit* covers a rather large area, the new *unit* takes the lower height; otherwise, it takes the higher one. We propose a criterion as below:

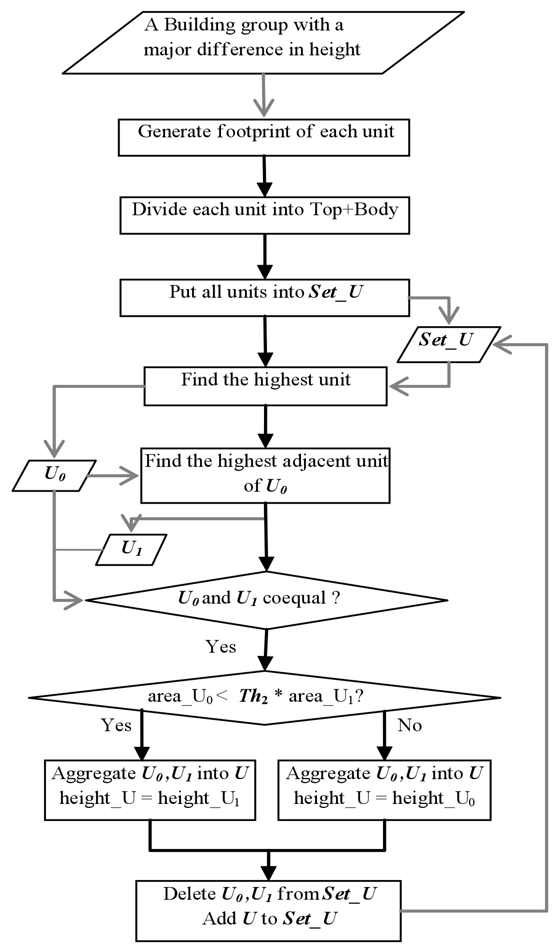

Figure 5. The main flow of the generalization algorithm for a building group with a major difference in height

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Given $\boldsymbol{a_1}$, $\boldsymbol{a_2}$, *and* $\boldsymbol{h_1}$, $\boldsymbol{h_2}$ ($\boldsymbol{h_1} < \boldsymbol{h_2}$) *as the areas and heights of two coequal units, the height of new merged unit* $\boldsymbol{h_3}$ *is determined as in (2), where* $\boldsymbol{Th_2}$ *is a predefined variable as the threshold.*

$$h_3 = \begin{cases} h_1 ; a_1 \geq Th_2 \bullet a_2 \\ h_2 ; a_1 < Th_2 \bullet a_2 \end{cases}, \quad (2)$$

The main flow of the algorithm is depicted in Figure 5.

V. EXPERIMENTATION AND RESULTS

The footprint-based generalization approach presented in Section IV will be tested on two sets of building groups.

A. Generalization of Building Groups with a Minor Difference in Height

The algorithm presented in Section IV-C is tested on a building consisting of 381 *units*. The results are shown in Figure 6, and the statistics are given in Table I.

TABLE I. STATISTICS1

Model	Footprint		3D model (percentage of the original)	
	Vertex	*Polygon*	*Vertex*	*Polygon*
Original	361	44	1565	381
GeoLoD3	186	18	843 (53.9%)	203 (53.3%)
GeoLoD2	121	3	679 (43.4%)	153 (40.2%)
GeoLoD1	121	3	590 (37.7%)	121 (31.8%)

B. Generalization of Building Groups with a Major Difference in Height

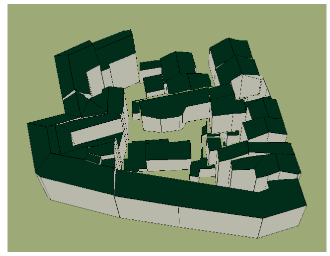
The algorithm presented in Section IV-D is tested on a building group consisting of 193 *units*. The results are shown in Figure 7, and the statistics are given in Table II. As for the threshold factor $\boldsymbol{Th_1}$ and $\boldsymbol{Th_2}$, we assign 2 to $\boldsymbol{Th_1}$, and 4 to $\boldsymbol{Th_2}$. Of course, other values could be assigned.

TABLE II. STATISTICS2

Model	Footprint		3D model (percentage of the original)	
	Vertex	*Polygon*	*Vertex*	*Polygon*
Original	193	19	879	211
Generalized	118	5	565 (64.3%)	116 (55%)

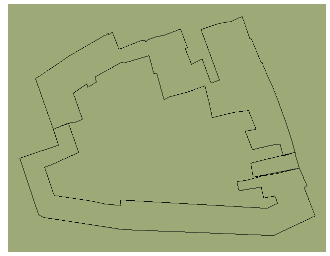
C. Generalization of Building Groups in 3D City Model

The approach is tested on a part of 3D city model of Nantes in France, which consists of 346 buildings (1536 *units*). The generalized result is shown in Figure 8. As we could see, both geometrical complexity and information density are reduced; meanwhile essential features are preserved and emphasized.

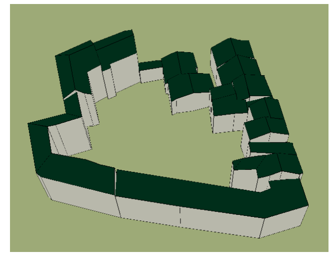


6a) Original model (© IGN BATI 3D)

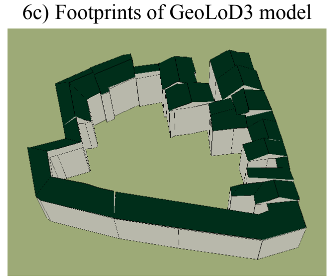
6b) Footprints of original model



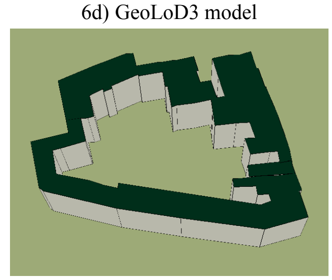
6c) Footprints of GeoLoD3 model



6d) GeoLoD3 model

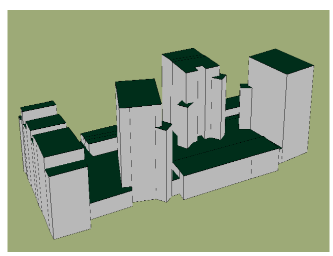


6e) GeoLoD2 model

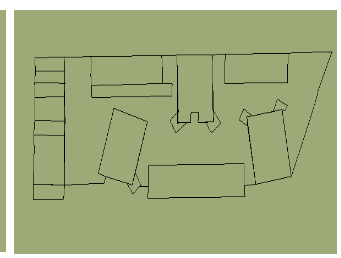


6f) GeoLoD1 model

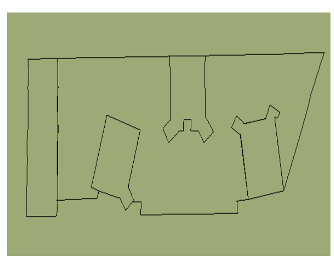
Figure 6. A generalization example of a building group with a minor difference in height



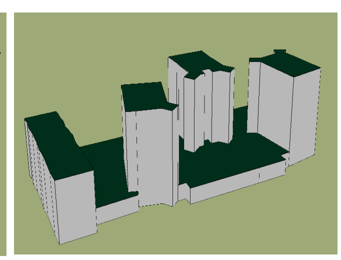
7a) Original model (© IGN BATI 3D)



7b) Footprints of original model

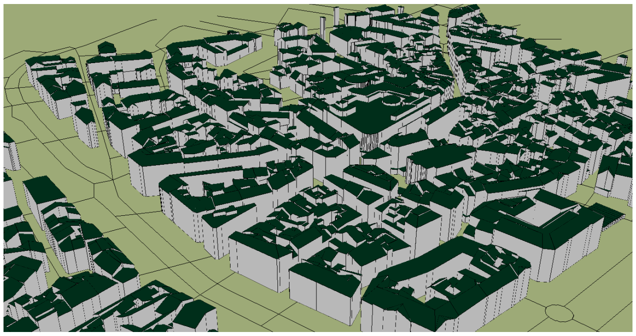


7c) Generalized footprints

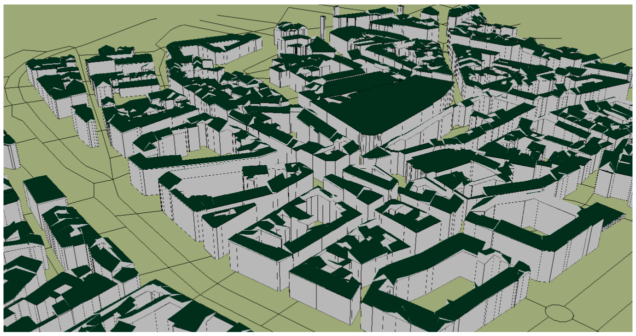


7d) Generalized model

Figure 7. A generalization example of a building group with a major difference in height



a) Original model (© IGN BATI 3D)



b) Generalized model

Figure 8. A generalization example of 3D city model

VI. CONCLUSION

This paper presented a novel approach for generalizing 3D building groups. The goal is to reduce both geometric complexity and information density, meanwhile maintaining recognizability, which requires at least LoD2 models. The emphasis has been placed on translating 3D generalization issues into 2D scope via footprints. First of all, a meaningful partition was suggested so that each footprint can carry feature information. A set of partition rules was developed for partitioning the buildings modeled by CityGML at LoD2.

Footprint-based generalization is then confronted with the difficulty of roof generalization. Unlike the existing approaches such as primitive matching, we proposed to divide a building into *Top* + *Body*. Thus, *Top* part can be easily transplanted onto the extruded model by displacement.

Two types of building groups were addressed in this paper: one has major difference in height and the other has minor difference in height. For the former one, we believe its outer feature can represent the whole group to a certain extent. For the latter one, it should not be handled as a whole. An iterative aggregation process is performed by comparing the height and area of every two adjacent units starting from the highest one.

The approach was tested on two building groups and a part of 3D city model. Group generalization shows its advantage in reducing information density, e.g. by eliminating insignificant buildings. Different from the methods only handle LoD1 block models [13, 14], our approach can handle LoD2 models as well. Instead of aggregating detailed models directly into LoD1 blocks [15], our approach supports generalization of geographical LoDs, thereby achieving data reduction and maintaining recognizability at the same time.

However, only connected buildings have been handled and only two types of building groups have been addressed. More studies are needed for dealing with complex cases. Coarser levels (including addressing the issue whether 3D is still necessary) will also be studied.

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